A true-time-delay transmit/receive module for X-band subarray phased arrays

Yunchuan Guo^{1a)}, Chengwei Shang², Kun Liu³, Lei Wang¹,
Xiansuo Liu¹, Yuehang Xu¹, and Tiedi Zhang¹

¹ School of Electronic Engineering, University of Electronic Science and Technology of China,

No. 2006, Xiyuan Ave, West Hi-Tech Zone, 611731, Chengdu, Sichuan, China

² Anhui Sun Create Electronics Co., Ltd.,

No. 199, Xiangzhang Street, High-tech Area, 230088, Hefei, Anhui, China

³ Chengdu Integrated System Technology Co., Ltd.,

No. 5, Tianhong Road, West Hi-Tech Zone, 610097, Chengdu, Sichuan, China

a) yycguo@uestc.edu.cn

Abstract: This letter presents the implementation of a 6-bit true-time-delay (TTD) transmit/receive (T/R) module in X-band. Improved phase linearity is achieved by using thin film coplanar waveguide transmission lines than traditional microstrip lines or lumped LC components of the most other TTD designs. In order to meet the requirement of the large dynamic temperature range in practice, the hybrid coupler reflective phase shifters with varactor diodes are adopted in long-time-delay units as temperature compensations for thermal phase drift. Experimental results of this TTD T/R module are carried out within a bandwidth of 1.2 GHz at X-band. The gain flatness is better than 1 dB and RMSE of the phase errors is less than 7° in all the transmitting and receiving delay states.

Keywords: coplanar waveguide, phased array, phase shifter, transmit/receive module, true time delay (TTD)

Classification: Microwave and millimeter-wave devices, circuits, and modules

References

- [1] R. Rotman, *et al.*: “True time delay in phased arrays,” *Proc. IEEE* **104** (2016) 504 (DOI: [10.1109/JPROC.2016.2515122](https://doi.org/10.1109/JPROC.2016.2515122)).
- [2] S. K. Garakoui, *et al.*: “Compact cascadable gm-C all-pass true time delay cell with reduced delay variation over frequency,” *IEEE J. Solid-State Circuits* **50** (2015) 693 (DOI: [10.1109/JSSC.2015.2390214](https://doi.org/10.1109/JSSC.2015.2390214)).
- [3] Y. Tian, *et al.*: “A 390 ps on-wafer true-time-delay line developed by a novel micro-coax technology,” *IEEE Microw. Wireless Compon. Lett.* **24** (2014) 233 (DOI: [10.1109/LMWC.2013.2296294](https://doi.org/10.1109/LMWC.2013.2296294)).
- [4] C. Cheung, *et al.*: “Time delay digital beamforming for wideband pulsed radar implementation,” *Proc. IEEE Int. Symp. Phased Array Syst. Technol.* (2013) 448 (DOI: [10.1109/ARRAY.2013.6731869](https://doi.org/10.1109/ARRAY.2013.6731869)).
- [5] M. Longbrake: “True time-delay beamsteering for radar,” *Proc. IEEE*

- NAECON (2012) 246 (DOI: [10.1109/NAECON.2012.6531062](https://doi.org/10.1109/NAECON.2012.6531062)).
- [6] T.-S. Chu, *et al.*: “An integrated ultra-wideband timed array receiver in 0.13 μm CMOS using a path-sharing true time delay architecture,” IEEE J. Solid-State Circuits **42** (2007) 2834 (DOI: [10.1109/JSSC.2007.908746](https://doi.org/10.1109/JSSC.2007.908746)).
- [7] T.-S. Chu and H. Hashemi: “True-time-delay-based multi-beam arrays,” IEEE Trans. Microw. Theory Techn. **61** (2013) 3072 (DOI: [10.1109/TMTT.2013.2271119](https://doi.org/10.1109/TMTT.2013.2271119)).
- [8] Q. Ma, *et al.*: “Silicon-based true-time-delay phased-array front-ends at Ka-band,” IEEE Trans. Microw. Theory Techn. **63** (2015) 2942 (DOI: [10.1109/TMTT.2015.2458326](https://doi.org/10.1109/TMTT.2015.2458326)).
- [9] F. Hu and K. Mouthaan: “A 1–20 GHz 400 ps true-time delay with small delay error in 0.13 μm CMOS for broadband phased array antennas,” IEEE MTT-S Int. Microw. Symp. Dig. (2015) 1 (DOI: [10.1109/MWSYM.2015.7166834](https://doi.org/10.1109/MWSYM.2015.7166834)).
- [10] H. Veenstra, *et al.*: “A 3-channel true-time delay transmitter for 60 GHz radar-beamforming applications,” Proc. ESSCIRC (2011) 143 (DOI: [10.1109/ESSCIRC.2011.6044885](https://doi.org/10.1109/ESSCIRC.2011.6044885)).
- [11] J. F. White: *Semiconductor Control* (Artech House, Dedham, 1977).

1 Introduction

With the increasing demand of broad bandwidth and wide scanning angle, true time delay (TTD) technique is becoming popular in phased array systems such as active electronically scanned array (AESA) radars [1, 2, 3, 4, 5]. Scanning angles of a phased array and a TTD array are implied in (1). For narrow-band applications, the phased array controls the scanning angle without significant degradation. However, a beam squint as a function of frequency will occur when the working frequency band is relatively wide. A TTD array steers the scanning beam by controlling the time difference of the wave traveling from the neighboring elements to the wave front. Compared with the traditional arrays with phase shifters, the TTD arrays overcome the beam squint, which can provide higher resolutions, farther distances, and wider scan angles when tracking and imaging.

Phased Array:

$$\theta = \sin^{-1} \left(\frac{\lambda \Delta \varphi}{2\pi \cdot Nd} \right) = \sin^{-1} \left(\frac{c \Delta \varphi}{2\pi f \cdot Nd} \right)$$

TTD Array:

$$\theta = \sin^{-1} \left(\frac{c \Delta \tau}{Nd} \right) \quad (1)$$

Although the TTD arrays have such superior performance, it is difficult to make them compact enough to fit the system requirement of size limitation, because the electrical length of the total delay is usually equal to many times of the wavelength. A number of works about TTD ICs have been reported [6, 7, 8, 9, 10]. Meander microstrip lines and lumped LC components are used in these works to bring about the time delay in very limited chip size. However, because of the dispersion effect of microstrip lines and lumped LC components, these TTD ICs are lack of enough phase linearity in high frequency range. This makes the array showing poor tracking sensitivity or low imaging resolution. As a compromise, subarray archi-

structures are usually adopted especially in large area and multi-functional phased arrays. With this architecture, the whole array is divided into several subarray sectors. Each sector has a hybrid TTD transmit/receive (T/R) module which provides accurate sector-level delay and serves for a number of front-end TTD or phase-shifting T/R ICs through a feeding network.

In this letter, we present a 6-bit TTD T/R module for X-band subarray application. Coplanar waveguide transmission lines are used to provide a better phase linearity than the microstrip transmission lines or the lumped LC components and a smaller bulk size than the coax transmission lines. The total delay of this TTD T/R module is 6702.1 ps with 106.4 ps step, which corresponds to 63λ in total and 1λ in each step at center frequency 9.4 GHz. The measured gain flatness is better than 1 dB and RMSE of the phase errors is less than 7° in all the transmitting and receiving delay states.

2 Phase linearity of coplanar waveguide time delay units

The time delay units were fabricated with thin-film coplanar waveguides on 0.254 mm-thick Al_2O_3 ceramic substrates. The coplanar waveguide transmission line is composed of meander strip line and surrounding ground with closely placed vias (spacing of 1 mm to 1.5 mm) to support non-dispersive transmission for high frequency (Fig. 1). Considering the mechanical strength of the ceramic substrates, we only designed four basic time delay units for 106.4 ps, 212.8 ps, 425.5 ps and 851.1 ps delays. The substrate sizes are $10 \times 6 \text{ mm}^2$, $10 \times 6 \text{ mm}^2$, $14 \times 6 \text{ mm}^2$ and $14 \times 10 \text{ mm}^2$ respectively. The longer time delay units for 1702.1 ps and 3404.3 ps were butted with two and four largest basic units.

Fig. 1. Coplanar waveguide transmission line units for (a) 106.4 ps (1λ at 9.4 GHz) delay, (b) 212.8 ps (2λ at 9.4 GHz) delay, (c) 425.5 ps (4λ at 9.4 GHz) delay, and (d) 851.1 ps (8λ at 9.4 GHz) delay.

From the tradition of phased arrays, phase linearity is often studied instead of time delay for TTD arrays. Thus, we also identify the time delay units here as 1λ unit, 2λ unit, 4λ unit, 8λ unit, 16λ unit, and 32λ unit according to the center frequency of 9.4 GHz. Fig. 2 presents the simulated phase errors to an ideal linear transmission of the 8λ -long coplanar waveguide in Fig. 1 and an 8λ -long microstrip line with similar substrate size. The results show that this compact coplanar waveguide transmission line has a better phase linearity than its microstrip counterpart. This indicates that this kind of time delay units is a candidate to compose of the 6-bit (63λ or 6702.1 ps delay totally) TTD T/R module for subarray sector with a very good phase linearity.

Fig. 2. Phase errors of the 8λ -long microstrip line and the 8λ -long coplanar waveguide to an ideal linear transmission.

3 Compensation for thermal phase drift

Another important performance of phased arrays especially in high-power and airborne radar system is the phase stability in large dynamic temperature range. Most of the passive components have the property of expansion and contraction. This is particularly significant for TTD arrays, because they are composed of transmission lines of many wavelength long. On our own experience, phase drift could be more than 1° per 1000° -delay when the temperature changes 10°C for coplanar waveguides on Al_2O_3 ceramic substrate at this frequency.

In order to meet the requirement of the large dynamic temperature range, the hybrid coupler reflective phase shifters with varactor diodes, as shown in Fig. 3a, are applied in long-time-delay units as phase compensations [11]. When the module temperature changes, the bias voltage applied to the varactor diode is tuned by a temperature sensitive resistor. Compensatory phase $\Delta\theta_c$ is then added to the delay line to cancel the thermal phase drift. Actually, the hybrid coupler reflective phase shifters are applied in pair. The compensatory phase $\Delta\theta_c$ is contributed by the phase shifter in the delay branch for $\Delta\theta_c/2$ and the phase shifter in the reference branch for $-\Delta\theta_c/2$ (Fig. 3b). This because the phase response of the hybrid coupler

(a)

(b)

Fig. 3. (a) Topology of the hybrid coupler reflective phase shifter. (b) Photograph of the 16λ time-delay unit with temperature compensation.

reflective phase shifter changes little when the bias voltage varies, and the phase distortions introduced by the phase shifter in each branch will cancel each other with this topology. Measured results of the thermal phase drift of the 16λ time-delay unit are shown in Fig. 4, which indicates the thermal phase drift is significantly weakened when the compensations are applied.

Fig. 4. Comparison results of the thermal phase drift (relative to 20°C) of the 16λ time-delay unit with and without compensations.

4 Measurements of the TTD T/R module

Topology and photograph of the X-band 6-bit TTD T/R module are presented in Fig. 5. Measured transmission coefficients of this module for the receiving and the transmitting states are shown in Fig. 6. Within a bandwidth of 1.2 GHz at X-band, the gain flatness is better than 1 dB for all the delay states when receiving and transmitting. Measured phase delay response of this TTD T/R module for the main delay states is shown in Fig. 7a. Fig. 7b shows that RMSEs of the phase errors are

(a)

(b)

Fig. 5. (a) Topology and (b) photograph of the X-band 6-bit TTD T/R module.

less than 7° compared with the ideal transmission line. This indicates a good phase linearity of this TTD T/R module in all the 6-bit transmitting and receiving delay states.

Fig. 6. Measured transmission coefficients of the TTD T/R module for (a) the main receiving states and (b) transmitting states.

Fig. 7. (a) Measured phase delays of the TTD T/R module for the main delay states. (b) RMSE of phase linearity of the TTD T/R module for all delay states.

5 Conclusions

This letter presents the implementation of a 6-bit TTD T/R module in X-band. Using the coplanar waveguide transmission lines as time delay units and hybrid coupler reflective phase shifters as phase drift compensations, this module shows good high-phase-linearity and thermal-stability, and is suitable for large and multi-functional subarray phased array applications.